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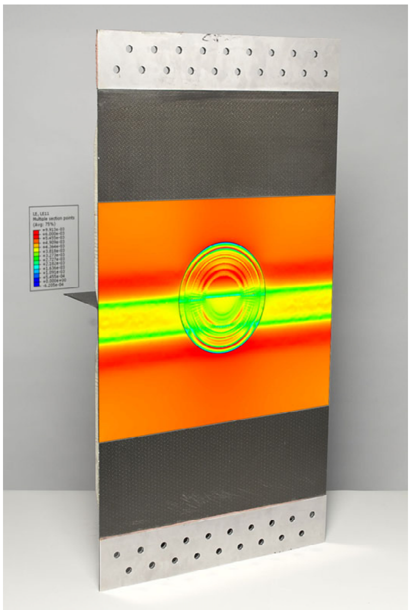
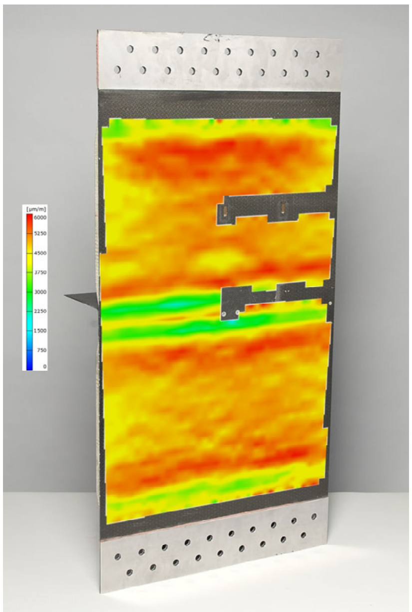
Executive summary

Design and manufacture of bonded composite repairs





Problem area

Due to the increased use of composite materials in aircraft structures, the number of damage occurrences in composite structures is expected to rise. Whereas in the past composites have been mainly applied in secondary components, they are now also used in the primary airframe structure. The repair of these load-carrying structures must restore both strength and stiffness. In this case, bonded repairs are pre-eminently suited, as they do not introduce extra bolt holes, do not add extra stiffness and are more efficient than bolted repairs in relatively thin laminates, as often applied in sandwich structures.

Description of work

Two design tools for bonded joints were developed. The first one calculates the shear and peel stress in a 2D cross-section of the joint, including geometrical non-linear behaviour and adhesive plasticity. This tool is used for the first dimensioning of the joint. The second tool is FE-based and is used to investigate possible 3D effects in the structure, such as load redistribution around the repair.

Tests were performed on the coupon level, on the element level (flat plates), and on a full-scale sandwich panel. The coupon tests were used to derive failure criteria and design guidelines, and to

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Author(s)
R.J.C. Creemers

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validate the 2D design tool. The element tests were used to evaluate different manufacturing processes (e.g. co-bonding, secondary bonding) and repair geometries (e.g. stepped or tapered scarf repairs). Finally, the full-scale component test on a sandwich panel was used validate the FE- tool, and to verify the design of the repair.

Results and conclusions
The research shows that the simple 2D design tool, used to analyse a cross-section of the repair, is fairly accurate, and is suitable for the dimensioning of repair in the first design phase.
Further, it is shown that even for complex structural features, such as a sandwich structure in its support area, a bonded composite repair can be designed which fully restores both strength and stiffness of the original structure.

Applicability
The design and analysis tools can be applied in the design of any adhesively bonded joint; both metals and composite joints can be analysed. They are therefore not limited to aerospace, but can also be used in civil applications. The 2D tool is fast, but the 3D joint geometry has to be simplified into a 2D analysis. It is therefore very suitable to be used in the (early) design process. For detailed stress determination of a 3D joint, finite element analyses are recommended.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Design and manufacture of bonded composite repairs

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Summary

Due to the increased use of composite materials in aircraft structures, the number of damage occurrences in composite structures is expected to rise as well. Whereas in the past composites have been mainly applied in secondary components, they are now also used in the primary airframe structure. The repair of these load-carrying structures must restore both strength and stiffness. In this case, bonded repairs are pre-eminently suited, as they do not introduce extra bolt holes, do not add extra stiffness, and are more efficient than bolted repairs in relatively thin laminates as often applied in sandwich structures.

Two design tools for bonded joints were developed. The first one calculates the shear and peel stress in a 2D cross-section of the joint, including geometrical non-linear behaviour and adhesive plasticity. The tool is used for the first dimensioning of the joint. The second tool is FE-based and is used to investigate possible 3D effects in the structure, such as load redistribution around the repair.

Tests were performed on the coupon level, on the element level (flat plates), and on a full-scale sandwich panel. The coupon tests were used to derive failure criteria and design guidelines, and to validate the 2D design tool. The element tests were used to evaluate different manufacturing processes (e.g. co-bonding, secondary bonding) and repair geometries (e.g. stepped or tapered scarf repairs). Finally, the full-scale component test on a sandwich panel was used to validate the FE- tool, and to verify the design of the repair. The research shows that even for complex structural features a bonded composite repair can be designed which fully restores both strength and stiffness of the original structure.

Contents

Abbreviations

CACRC	Commercial Aircraft Composite Repair Committee
DIC	Digital Image Correlation
FE	Finite Element
LL	Limit Load
SERR	Strain Energy Release Rate
UL	Ultimate Load
VBA	Visual Basic for Applications

1 Introduction

The Dutch Ministry of Defence (Defence Materiel Organization) initiated a National Technology Programme on inspection and repair of composite structures, as they recognized that the majority of their (future) military aircraft will contain composite materials in the structural airframe (NH90 and F-35). The aim of the research programme, carried out by the NLR, was to develop tools and procedures for inspection and repair of composite structures. With respect to repair, the research was aimed at bonded repairs. A bonded repair does not add extra stiffness, because composites offer the possibility of a ply-by-ply replacement of the damaged material. Further, a bonded repair does not require bolt holes with the associated stress concentrations. Especially for very thin laminates (e.g. in sandwich structures) load introduction through bolts is structurally very inefficient, if possible at all.
It is recognized that in civil aviation bonded repairs are not certifiable yet in primary single load-path structures due to a lack of reliable inspection techniques. However, efforts in this field are undertaken worldwide to overcome these problems (Ref. 1).

2 Design tools

Two analysis tools for the design of bonded joints were developed. The first one analyses only a 2D cross-section of the joint and is used for the first dimensioning of the repair. The second tool is FE-based (Abaqus) and is used to determine 3D effects, such as load redistribution around the repair.

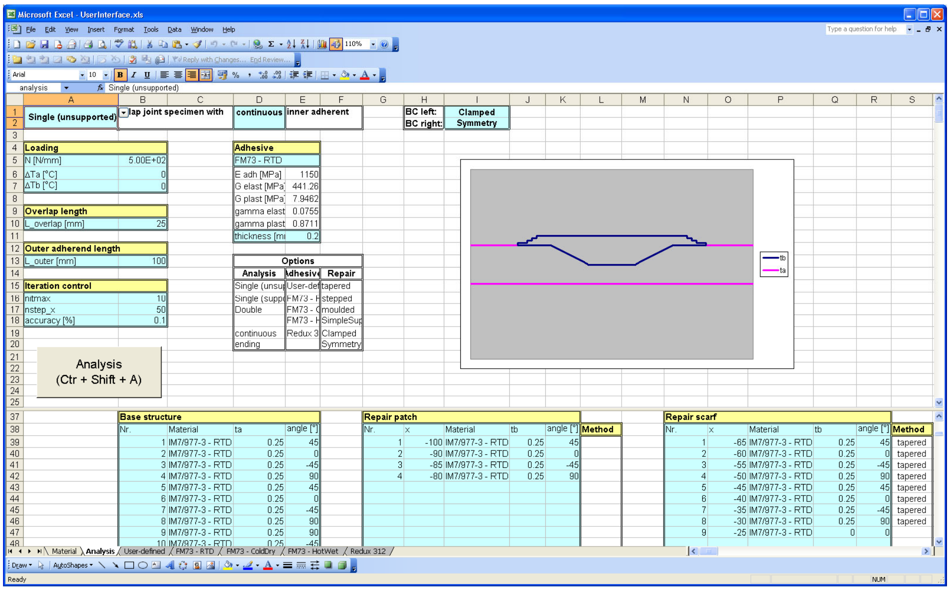

Figure 1 Excel tool for analysis of a 2D cross-section of a bonded joint

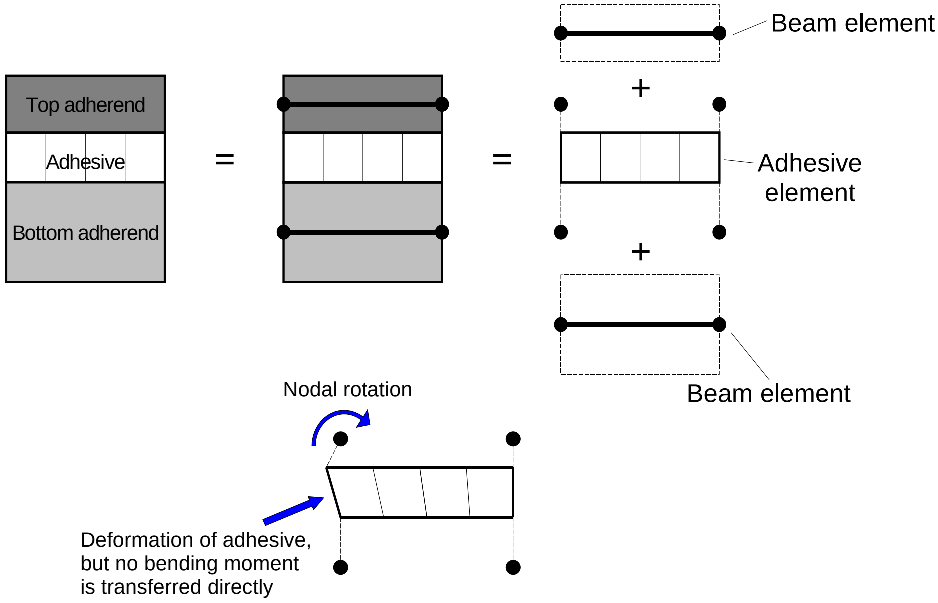

Figure 2 FE discretization of a bonded joint into beam and adhesive elements

The 2D joint analysis is programmed in VBA and runs within Microsoft Excel (Figure 1), which makes it very easy to use for anyone. It calculates the shear and peel stress in a 2D cross-section of the joint, including geometrically non-linear behaviour of the adherends and adhesive plasticity (using a bi-linear approximation). Previous versions were based on discretized procedure for beam elongation and deflection in combination with an iterative numerical solution procedure (Ref. 2). However, this was modified to an FE-formulation, which is faster and more robust. In the 2D analysis the adherends can be presented by beam elements, see Figure 2. A special-purpose non-linear beam element has been developed to cope more efficiently with the geometrically non-linear behaviour of the joint. Also, a specially developed adhesive element has been implemented with its nodes placed externally of its physical material location. The adhesive element can only transfer loads from one adherend to the other through shear and peeling forces. Bending moments or rotations are not transferred directly by the adhesive. However, they do affect the deformation of the beam and adhesive elements, as shown graphically in Figure 2. In the end, bending moments will be transferred via shear and peeling forces, which resembles a real life situation with relatively stiff adherends and a much more compliant adhesive.

3 Materials used

The material used to represent the base structure is HexPly M18/1 180 °C curing epoxy resin with the G939 fabric. As repair material HexPly M20 130 °C curing epoxy resin with the G904 fabric was selected. The lower curing temperature of the repair material ensures that the glass transition temperature of the base structure is not exceeded during the repair process. The same material has been chosen as a standardized repair material by the Commercial Aircraft Composite Repair Committee (CACRC). Redux 312/5 was selected as adhesive because of its high strength properties and its compatible curing temperature with HexPly M20. The adhesive has a woven nylon carrier for bond line thickness control.

4 Coupon tests

Figure 3 shows that many possible failure modes may occur in a bonded repair or a bonded joint in general. Tensile failure in any of the adherends usually only occurs at very high strain levels or due to excessive bending caused by eccentricities. Failures within the adhesive (cohesive failures) are extremely rare in real structures due to the large plastic range of the adhesive. More common are failures of the interface (or adhesive failures), e.g. due to bad surface treatment, and interlaminar failures in the adherend.

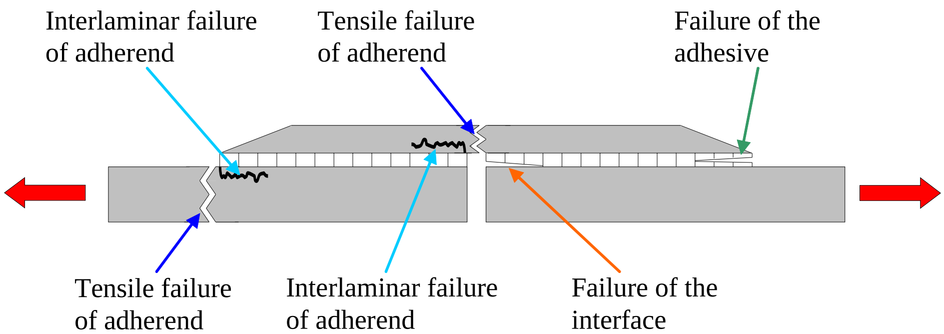

Figure 3 Failure modes in bonded composite joint

Although the strength of the adhesive is rarely critical, the stiffness properties are required as input for analysis and they determine to great extent the stress distribution in the adhesive onto the adherends. Two different tests have been performed on the adhesive, the flatwise tension test (ASTM D2094) to determine the peel strength and the thick adherend lap shear test (D5656) to determine the shear strength and stiffness of the adhesive.

4.1 Flatwise tension tests

First, the peel strength of the Redux 312/5 adhesive was determined separately based on six flatwise tension specimens with only adhesive in between the metal parts. The average peel strength of the adhesive was found to be 62 MPa. In a second configuration of the flatwise tension test, the interlaminar tension strength was determined for a pre-cured four ply laminate of HexPly M18/1/G939 material which was bonded in between two layers of adhesive to metal blocks (ASTM D7291). Basically, there are three possible failure locations for this test configuration: within the adhesive, within the laminate as an interlaminar tensile failure, or at the interface between laminate and adhesive, see Figure 3 as well. In this case, all specimens failed in interlaminar tension at a stress level of only 38 MPa (compared to 62 MPa for the adhesive). For HexPly M20/G904 similar values were found. It appears that the strength of the laminate in interlaminar tension mode is much smaller than the strength of the adhesive or of the interface between adhesive and composite laminate.

4.2 Thick adherend shear tests

The results of the thick adherend lap shear test are shown in Figure 4. The elastic shear stiffness of the adhesive is found to be 588 MPa. The maximum shear strength is 38 MPa which compares well to the manufacturer's data. It appears that, in the interlaminar shear mode, the strength of HexPly M18/1/G939 (70 MPa) and HexPly M20/G904 (78 MPa) is much higher than the strength of the adhesive. However, Figure 4 shows that the adhesive does have a very large plastic zone and must be loaded to very high strain levels before it actually fails. In reality these strain levels are only attained when very small overlap lengths are applied, otherwise different failure mechanisms occur earlier in the joint (e.g. interlaminar failure due to the combination of peel and interlaminar shear stresses).

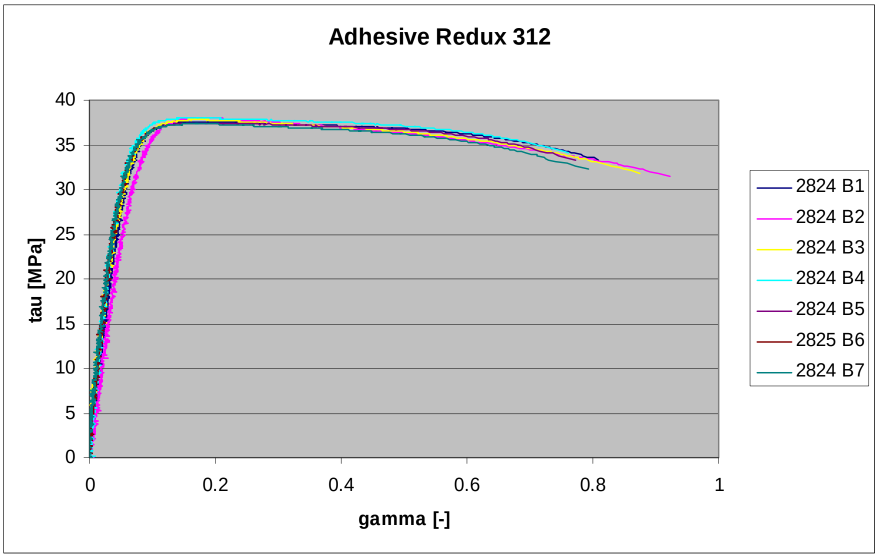

Figure 4 Shear stress vs. shear strain curve for Redux 312/5

4.3 Double-lap shear tests

Next, several configurations of double-lap shear specimens were tested in tension, see Figure 5. Both static and fatigue tests have been performed. In fatigue testing failure always initiated at the tip as an interlaminar crack running along the first ply in the base adherend. Also statically most failures initiated at the tip, but for a small number of specimens failure initiated at the butt-joint with the crack running in the doubler. Table 1 gives the stresses and strains in the adhesive as determined with the analysis tool presented above. These are also the stresses imposed by the adhesive onto the base adherend and doubler.

Due to adhesive plasticity, for all static tests the maximum shear stress on the adherends is 36.2 MPa, which is well below the interlaminar shear strength of the laminate. The peel stress varies from 38.9 MPa and 4.7 MPa to -18.6 MPa. These last two values are also well below the interlaminar tensile strength of the laminate. However, still failure occurs in an interlaminar mode. Apparently, there is some sort of interaction with the in-plane strain in the laminate. Table 1 shows that the lower the peel stress, the higher the allowable in-plane strain (at this shear stress level of 36 MPa). Clearly, to derive a criterion that can predict static failures in an interlaminar mode there is a need for a test set-up that introduces a well-defined combination of shear, peel and (the one which is often neglected) in-plane stress.

In fatigue, the specimens with short overlap never showed stable crack growth. The long specimens did show stable growth, albeit at a higher rate for specimens with the tapered doubler than for the stepped doubler. This is caused by the higher load required to initiate failure in the specimens with tapering. Next, with a crack starting at the tip the beneficial effect of tapering quickly disappears while the fatigue test is performed with a higher load. An energy approach such as Strain Energy Release Rate (SERR) is able to explain the damage growth behaviour of

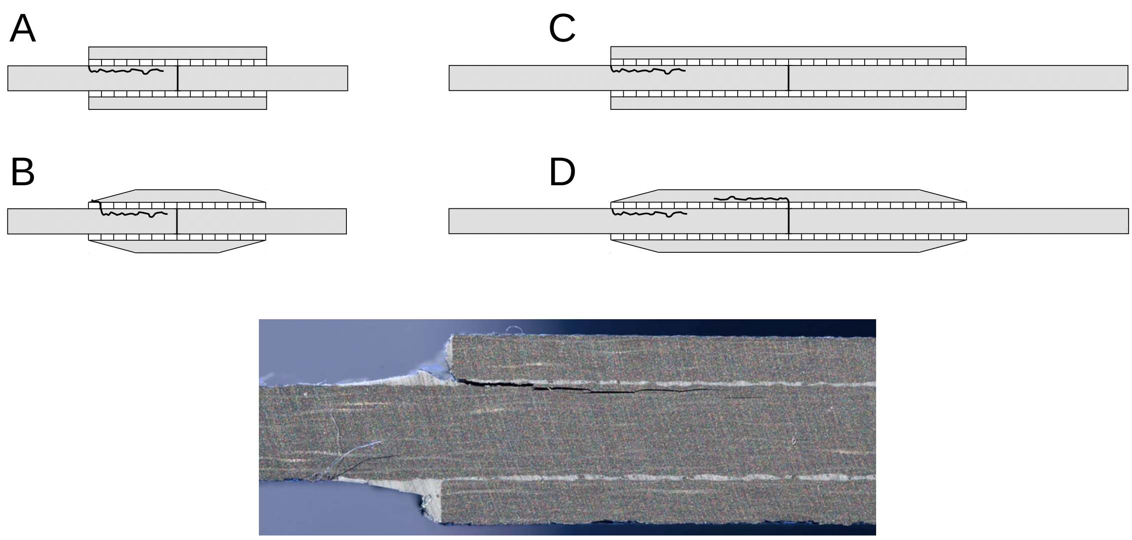

Figure 5 Test coupon configurations for static and fatigue tests

Table 1 Stresses and strains in the joint at crack initiation according to analysis tool

	Failure initiation: static test				
Specimen Config.	**Tensile load [kN]**	**Shear strain in adhesive [-]**	**Shear stress in adhesive [MPa]**	**Peel stress in adhesive [MPa]**	**Surface strain in adherend [με]**
A and C	23	0.102	36.2	38.9	5222
B and D	36	0.092	36.2	4.71	8285
D*	39	0.226	36.2	-18.6	9767
	Crack initiation: fatigue tests				
A and C	9.5	0.039	22.7	18.7	2157
B and D	12	0.026	15.3	2.0	2724

* Crack initiation at butt-joint

both the short specimens (continuously increasing SERR and damage growth rate) and long specimens (vanishing effect of tapering, subsequently stable growth). However, for damage initiation under fatigue loading a different criterion is required and the same remark applies as for the static failure criterion, i.e. the need for a test set-up that introduces a well-defined combination of shear, peel and in-plane stresses/strains.

5 Structural element tests

Flat plates with different repairs were used to evaluate manufacturing processes (co-bonding with and without adhesive vs. secondary bonding, autoclave pressure vs. vacuum) and repair geometries (stepped vs. tapered scarf repairs, with and without external patch, circular or oval repair, several scarf ratios).
None of the specimens with a scarf ratio of 1:20 in the loading direction failed in the repair area. They all failed outside the repair at the same strain level of 1.2% as the undamaged laminate without any signs of damage or plastic deformation in the adhesive. The specimens with a scarf ratio of 1:10 did fail in the repair area. No difference was found between the stepped and tapered scarf specimens. For 1:10 scarf repairs, application of an external patch may be beneficial, as long as it does not introduce too much eccentricity and bending.
A co-bonded repair with application of an adhesive layer clearly resulted in the highest failure loads. There was no significant difference between the repairs that were cured under autoclave pressure and the ones cured under vacuum. The co-bonded repair without adhesive between the repair and base panel failed at a lower load and in a much more sudden way than the repairs with adhesive (see failure sequence below). The epoxy resin, which forms the bond line in these specimens, is more brittle than the adhesive and does not have the ability to deform plastically,

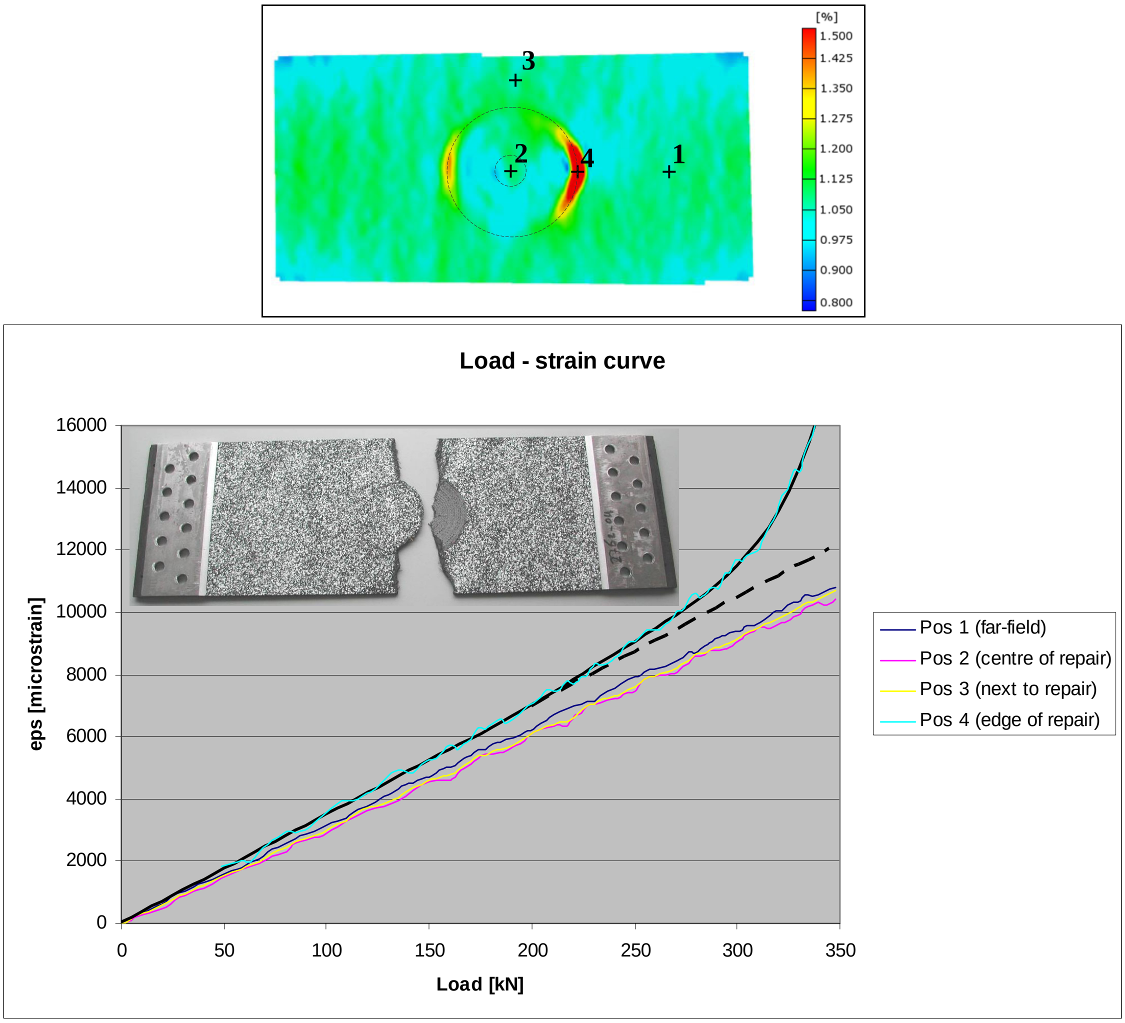

Figure 6 ARAMIS strain measurements for a flat plate with co-bonded scarf repair

thereby redistributing the load through the repair. Finally, the secondary bonded specimens all failed at lower load levels than the co-bonded repairs due to a poorly controlled bond line thickness. The secondary bonded repair is not recommended for use in practice, because it is very hard to achieve a tight fit between the two pre-cured parts in a real life 3D patch repair.

During the tests on the structural elements Digital Image Correlation (DIC) was used to monitor the strains in the entire specimen. This proved to be very valuable to reveal the failure sequence in these specimens. For the co-bonded scarf repairs with an adhesive layer, the failure sequence starts with a plastic zone developing in the adhesive. At its edge the patch is no longer capable to transfer additional load and starts to slide over the base panel. Although not a real strain value, this sliding behaviour is represented by the DIC measurement as a large strain at the edge of the repair (Figure 6). Due to the plastic zone, the load transfer through the repair patch

becomes less effective. This results in stress concentrations at the sides of the hole, which eventually initiates final failure.
The above described behaviour can be of help when designing a repair. Below Limit Load (LL) no large-scale permanent deformations of adhesive plasticity is allowed. However, after onset of plasticity there is still so much load capacity left in the repair, that final failure is still far away, i.e. if the LL requirement is satisfied, the Ultimate Load (UL) requirement is automatically satisfied as well (note that this only applies to environmental conditions in which the adhesive has a large plastic regime; at low temperatures the adhesive can be much more brittle). Further, comparison of the above-presented analysis tool with the test results shows that analysis of a 2D cross-section gives an accurate prediction for the onset of plasticity in the real 3D repair.

6 Full-scale test of a sandwich panel

A full-scale component test on a sandwich panel was performed to verify the design of the repair, which was based on the analysis results for a 2D cross-section, and to validate the Abaqus FE-tool. The sandwich panel was damaged in its chamfered region. Both the supporting rib and sandwich needed repair. Inner and outer skins were repaired with a bonded patch using one-sided access only. Figure 7 and Figure 8 show the repair concept.
The panel was tested up to a far-field strain of 5267 με. Based on similarity with the flat plates, the final failure strain is estimated to be much higher. With no signs of adhesive plasticity yet, a failure strain exceeding 8400 με is to be expected. Unfortunately, this could not be validated by test because the maximum load capacity of the test bench was reached. However, the strain level of 5267 με is already beyond the usual strain values in aerospace applications (3600 με in

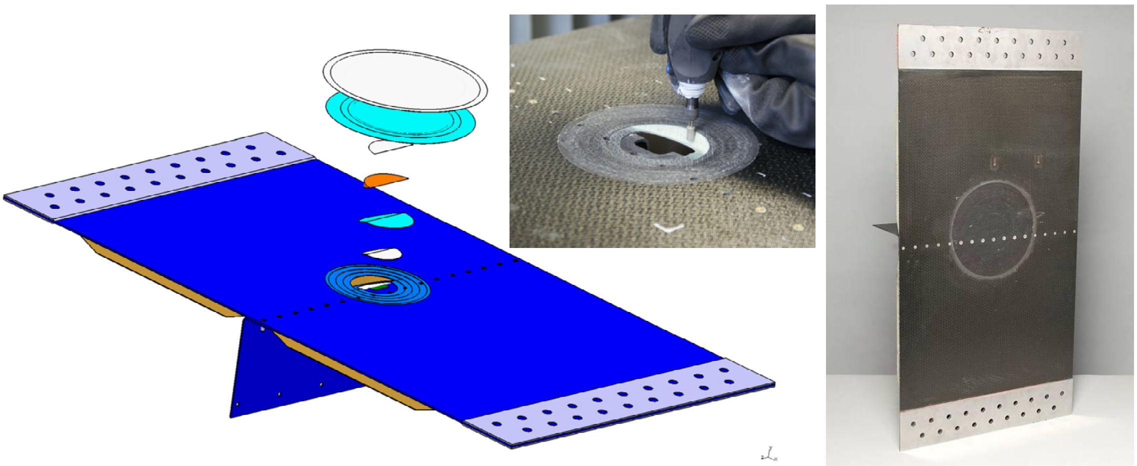

Figure 7 Repair concept for the damaged sandwich panel

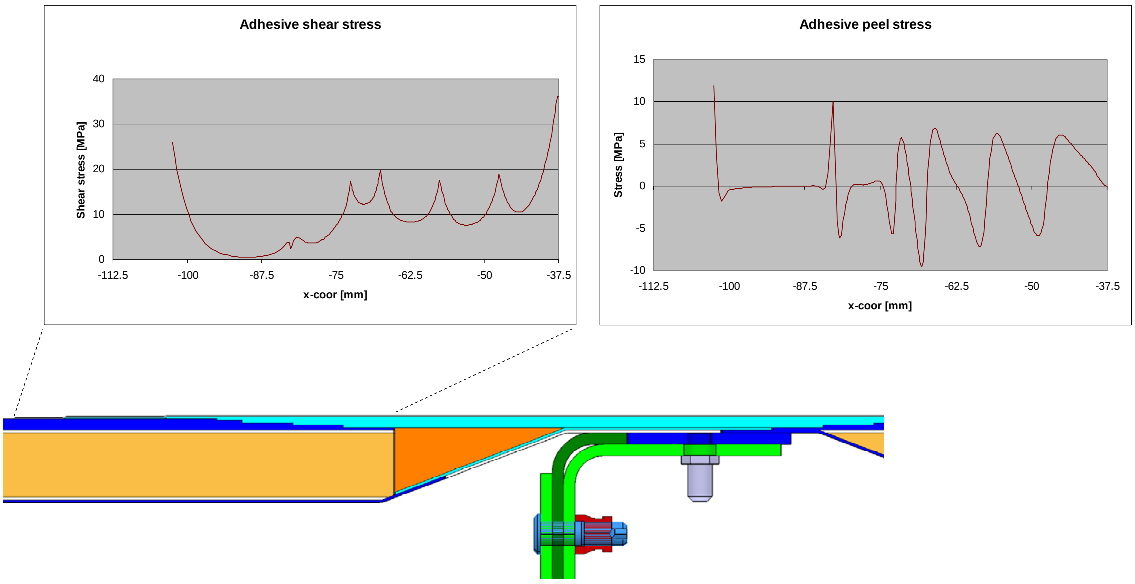

Figure 8 Analysis results for a cross-section of the repaired sandwich panel

tension at UL), and far beyond the usual design strains at LL (2400 με) at which no large scale plastic deformations are allowed.

Comparison of the FE-analysis results with strain measurements on the repaired panel shows excellent agreement (Figure 9). Further, no signs of load redistribution towards or around the repair could be detected. This shows that even for complex structural features a bonded composite repair can be designed which fully restores both strength and stiffness of the original structure.

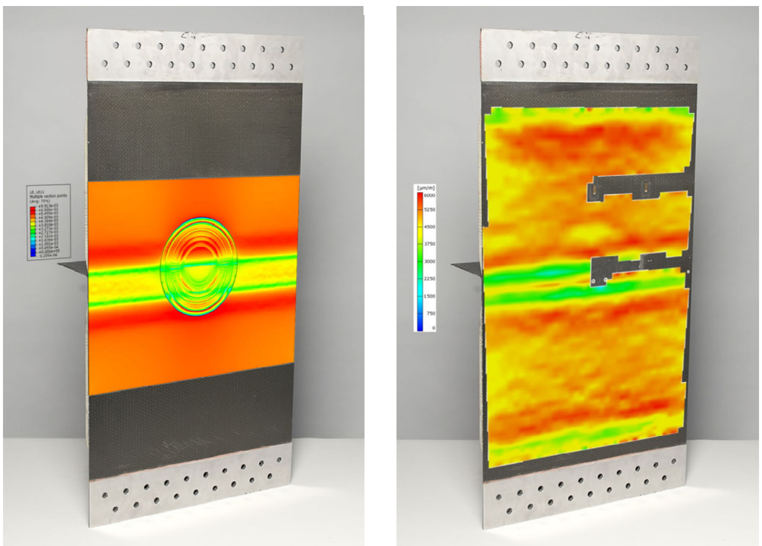

Figure 9 FE-analysis results (left) and ARAMIS strain measurements (right)

Conclusions

The results presented in this report clearly show the potential of bonded repairs. Even for complex structures, such as the chamfered area of a sandwich panel, a bonded repair concept can be designed that restores both strength and stiffness of the structure.
The test results on structural elements show that, for a well-performed repair, the adhesive itself is rarely critical. Most structural adhesives have a large plastic regime which allows for load redistribution. For a joint with relatively long overlaps and/or shallow scarf angles, the onset of plasticity occurs long before final failure. In general, a lot of capacity is left in real 3D joint after the first formation of a plastic zone. This implies that, when designing a bonded repair, the requirement of “no large-scale plastic deformations below Limit Load” will be the critical design driver. When this requirement is satisfied, the additional requirement of “no failure below Ultimate Load” is usually satisfied automatically too.
A much more common failure mode for a bonded joint is an interlaminar crack, either in the base adherend or within the repair laminate. These interlaminar failures (being a matrix dominated mode) are fatigue sensitive. However, slow growth is possible in this particular failure mode, but the joint must be designed for it by applying long enough overlap regions. Tapering of the patch at its ends does help to delay damage initiation, but once damage is present (as must be assumed in a damage tolerant design) the beneficial effect of this tapering quickly disappears.
Two design tools for bonded joints were developed. The first one calculates the shear and peel stress in a 2D cross-section of the joint, including geometrical non-linear behaviour and adhesive plasticity. The simplification into a 2D cross-section still gives a fairly accurate estimate of the strains and stresses in the 3D joint; the 2D tool is very effective in the (preliminary) design process. The second tool is FE-based and is used to investigate possible 3D effects in the structure, such as load redistribution around the repair, which cannot be captured by the 2D design tool.

Acknowledgement

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